The Cassini Mission: Reconstructing Thirteen Years of the Most Complex Gravity-Assist Trajectory Flown to Date

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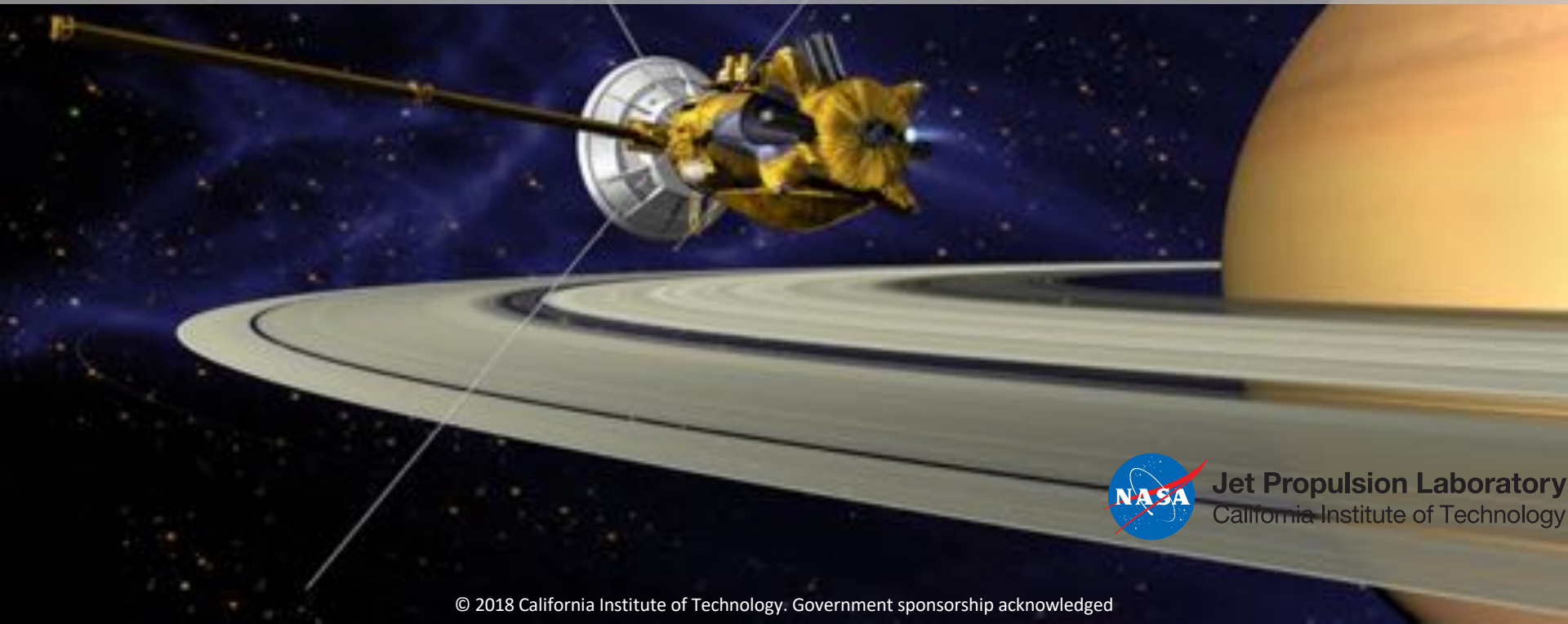

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California Institute of Technology

Overview

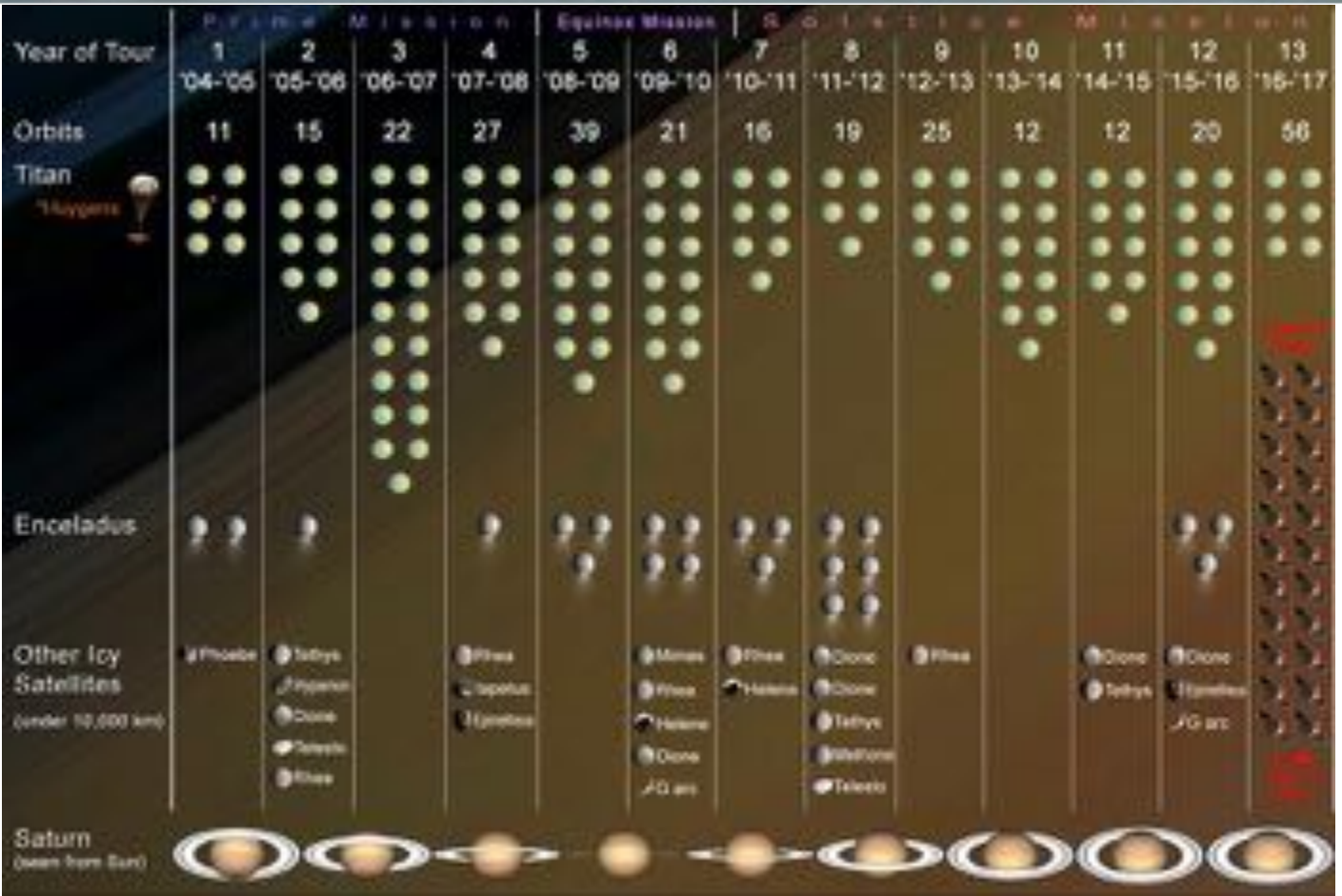
- A Brief History of Cassini
- Objective of this reconstruction

- Overview of Cassini Navigation
  - How do we navigate Cassini?
  - Orbit determination overview
  - Saturn system parameters variations over time
  - From operations to reconstruction
- Inputs Preparation
- Reconstruction Tool Layout

- Current Status and Results
  - Overall plans
  - Trajectory differences at Epoch
  - Optical navigation residuals

- Conclusions

A Brief History of Cassini



Some numbers…

Number of Targeted encounters: 163,

or about 1 every month

Number of Maneuvers: 360 executed out of 492 designed,

or 2.5 per month

Objective of this Reconstruction

- Cassini's trajectory reconstructions are already publicly available on the NAIF website.
  - Deliveries were made every few months as the mission progressed.

- **Objective for this reconstruction:**
  - **Simplify science data reduction (and thus redo all of reconstructions done during mission operations).**

- As the Saturn system and spacecraft error modeling were refined over the years, inputs to those reconstructions have also evolved. In particular, they include different models for Saturn's gravity, pole, and the ephemerides of ten of Saturn's moons.
  - At least 40 different models of the Saturn system were used, while the Orbit Determination team also estimated the Saturn system in between model upgrade.
  - → **Reconstructions include about 100 different Saturn's system models.**

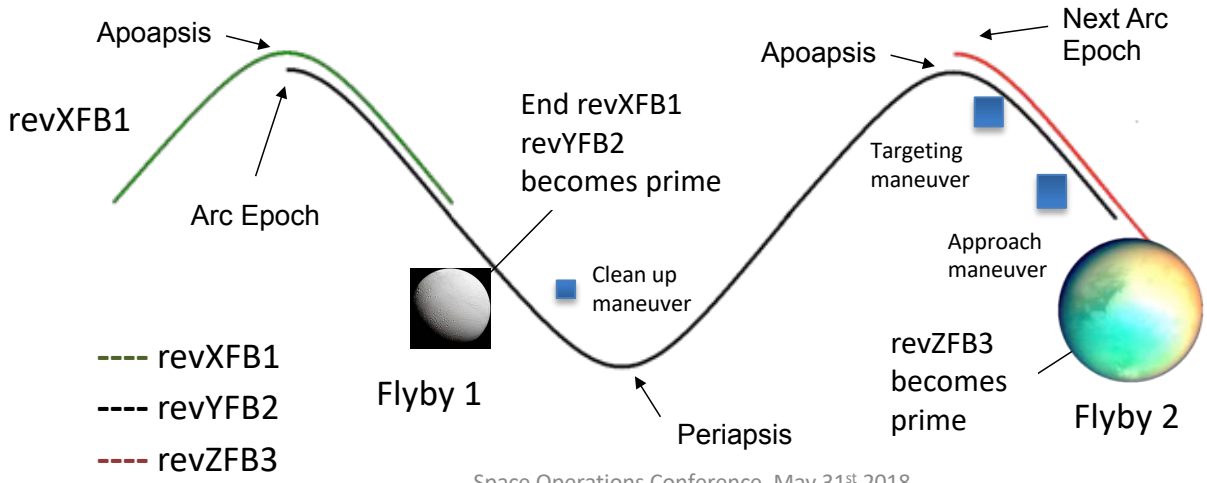
- **The main goal is to have a uniform, single model for the Saturn system.**
  - Working closely with the JPL Solar System Dynamics group to get latest models of Saturn's system.

- Challenges:
  - Thirteen years of data
  - Navigation process improved over time and got modernized through using a different navigation software

Cassini Navigation Overview

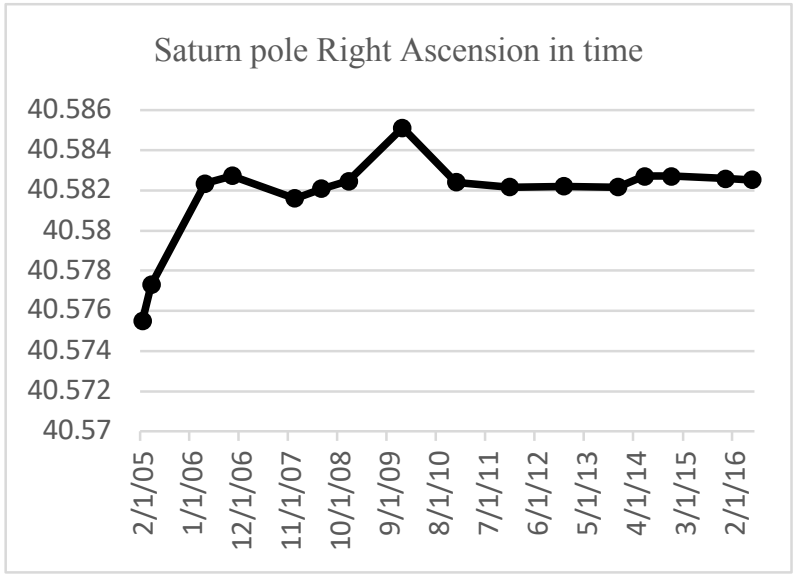
- The concept behind the Navigation team is to return the spacecraft to the reference trajectory for targeted flybys (or predetermined control points). This is implemented by:
  - Estimating the spacecraft trajectory and associated parameters with covariance.
  - Use this knowledge to compute trajectory correction maneuvers.
- Navigation analysis done over “arcs” focused on a particular targeted encounter.
- Trajectory deliveries included data from an arc Epoch to the next arc Epoch.

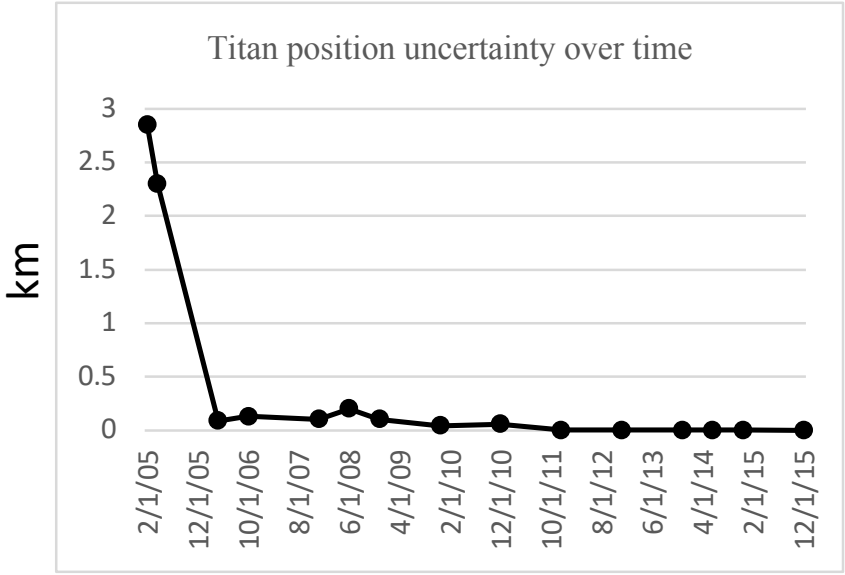
--> **implements this ops approach for re-reconstruction**



Saturn System Parameters' Variations over Time

- Optical images were also used to refine our overall knowledge of Saturn's system.
- A navigation filter was used to estimate selected spacecraft and Saturn's system parameters.
  - Saturn gravitational harmonic coefficients, pole angles, and satellites' states were estimated for certain periods of time.
  - Pole Right Ascension true uncertainty is larger than formal uncertainty from estimation; Declination motion negligible.
  - Titan position uncertainty indicates we should expect bigger changes early in the mission when comparing uniform reconstructions against reconstructions from operations.





From Operations to Uniform Reconstruction

- In total, 172 arcs were delivered during the mission.
- A number of papers have been published to describe the workings and performances of both the Orbit Determination and Flight Path Control teams.

- One of the requests for the uniform reconstruction was to keep the same epochs as the previous delivered reconstructions during the mission.
  - As a result, time allowed implementing the “arc” operational approach for the uniform reconstruction.

- Full mission reconstruction:
  - Epoch: just after Saturn Orbit Insertion (SOI), on July 1st 2004 14:00 ET.
  - End time includes the last data received from the spacecraft just before its disintegration into Saturn atmosphere on September 15th 2017 11:54 ET.

- For the uniform reconstruction effort, we were able to reduce the number of arcs to 157

Inputs Preparation

Inputs	Volume	Conversion characteristics
Tracking data (Deep Space Network)	~ 5000 passes	Merge all tracking data
Earth atmospheric calibrations	80000 entries, ionosphere 485000 entries, troposphere	Merge monthly calibration files into for each ionospheric and tropospheric calibrations
Radiometric data edits	10000 edits	Fetch and merge edits from 121 ODP arcs and 51 MONTE arcs
Optical images for navigation	2243	Directly ingested by MONTE (609 pre-SOI images not processed)
Small thruster events (turns, spacecraft momentum maintenance)	2253	Make a new file per arc, for all 157 arcs. Reset all *a priori* uncertainties
Encounters where thrusting was used	80	Query telemetry and build acceleration profile for each, verify begin and end turns for each, include stochastics at flyby.
Spacecraft attitude files	102	Convert sequence NAIF format attitude file (called c-kernel) to MONTE, adding two reconstructed attitude files for safings during SOI

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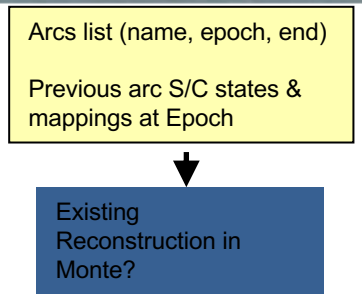

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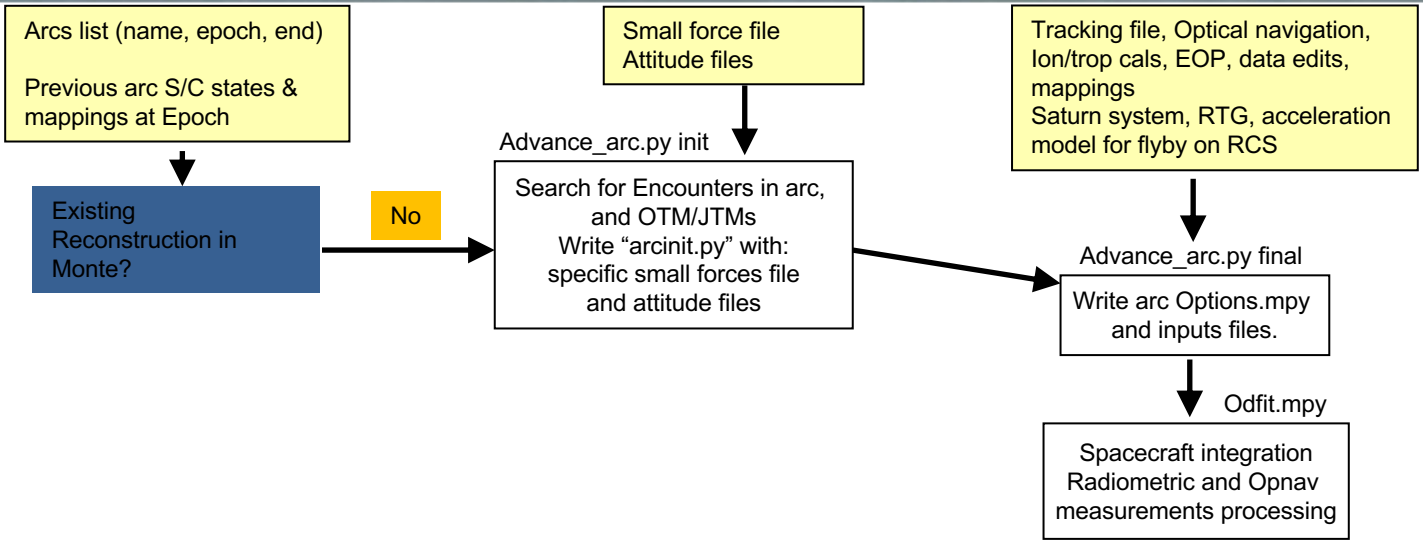

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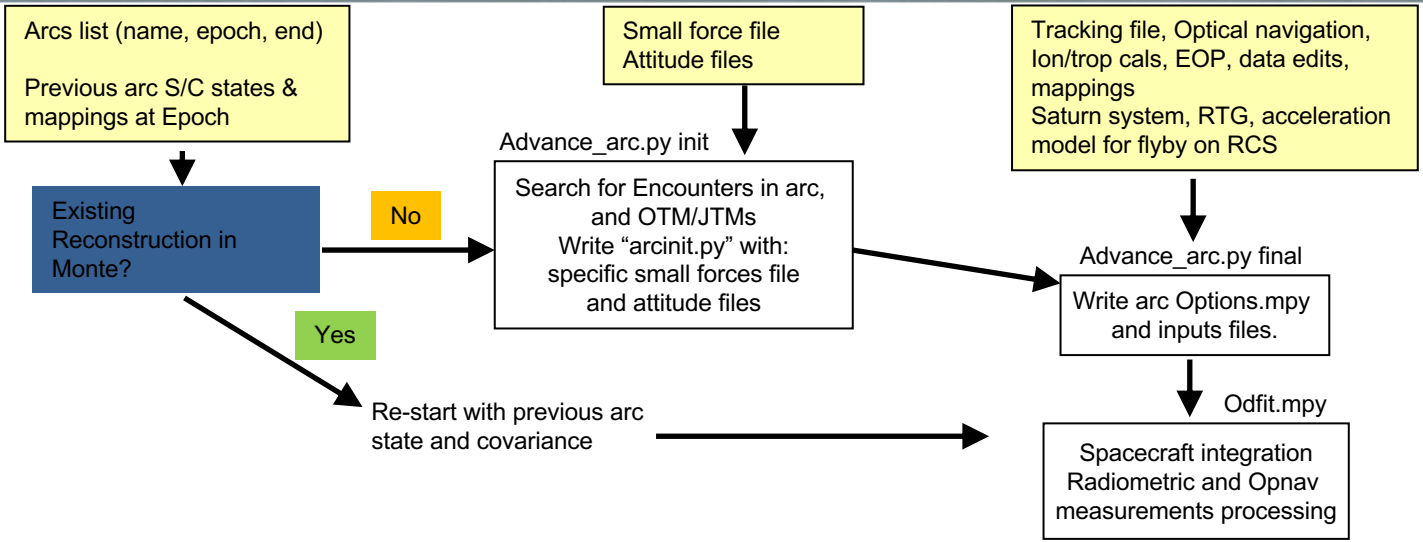

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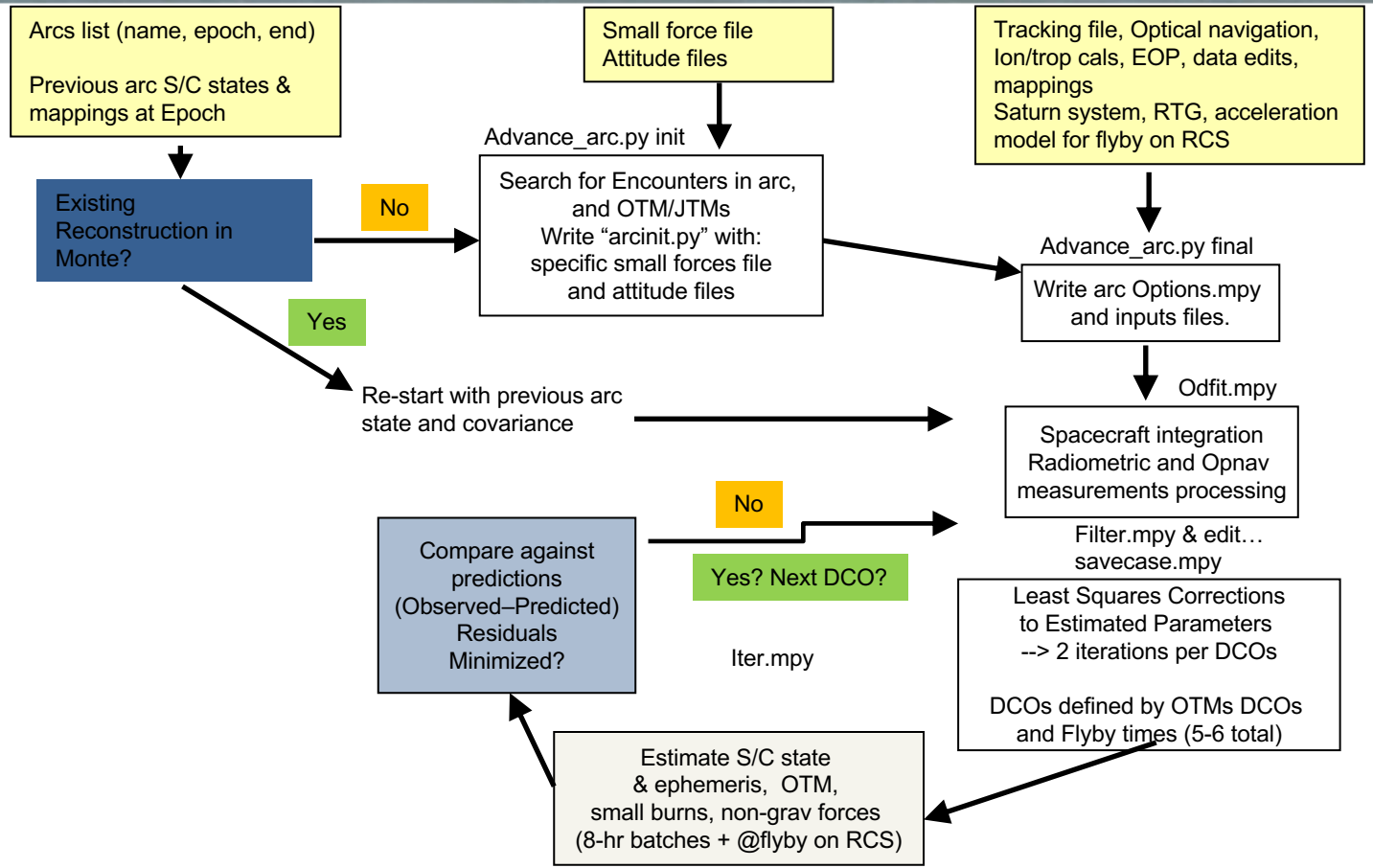

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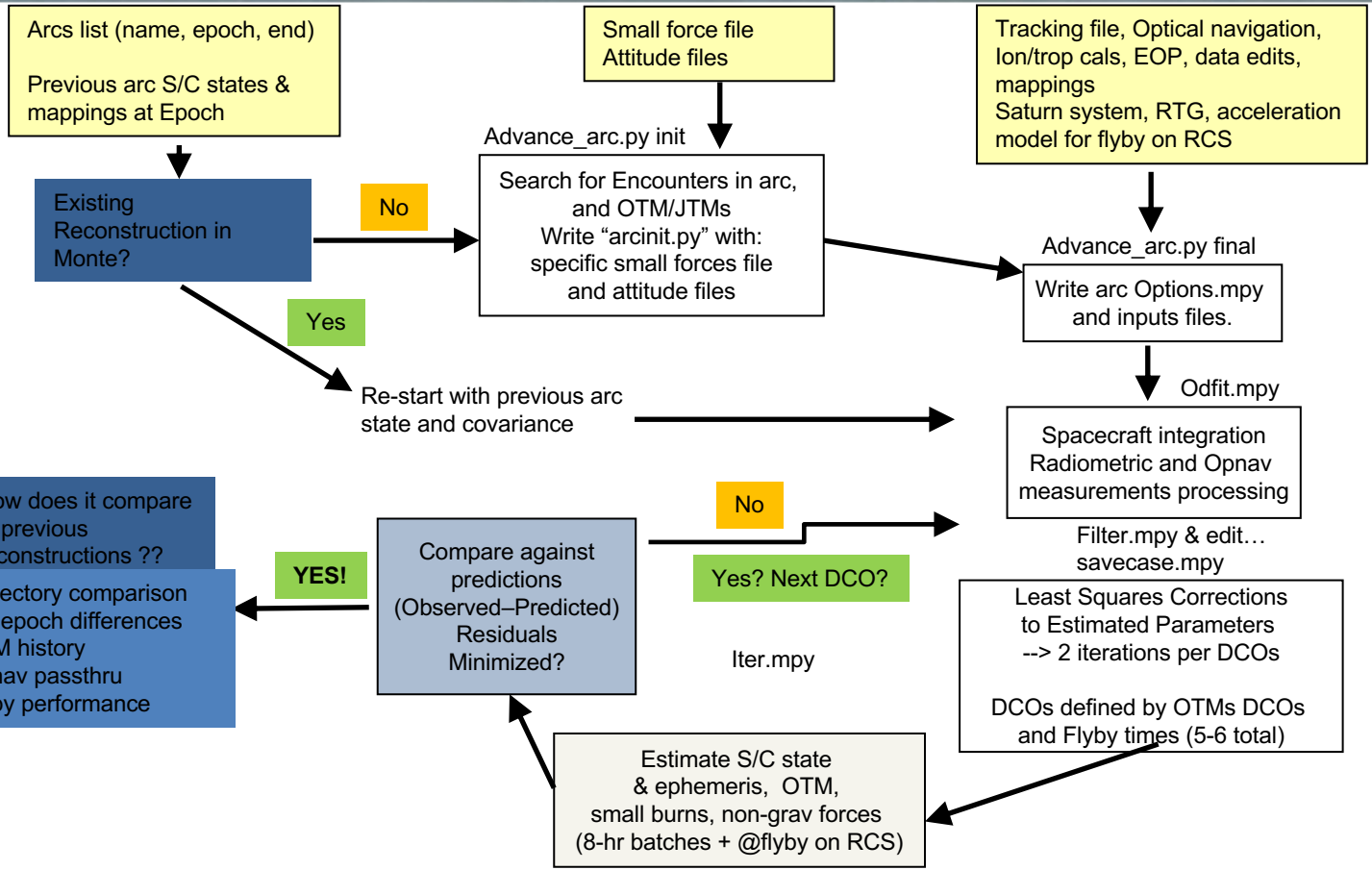
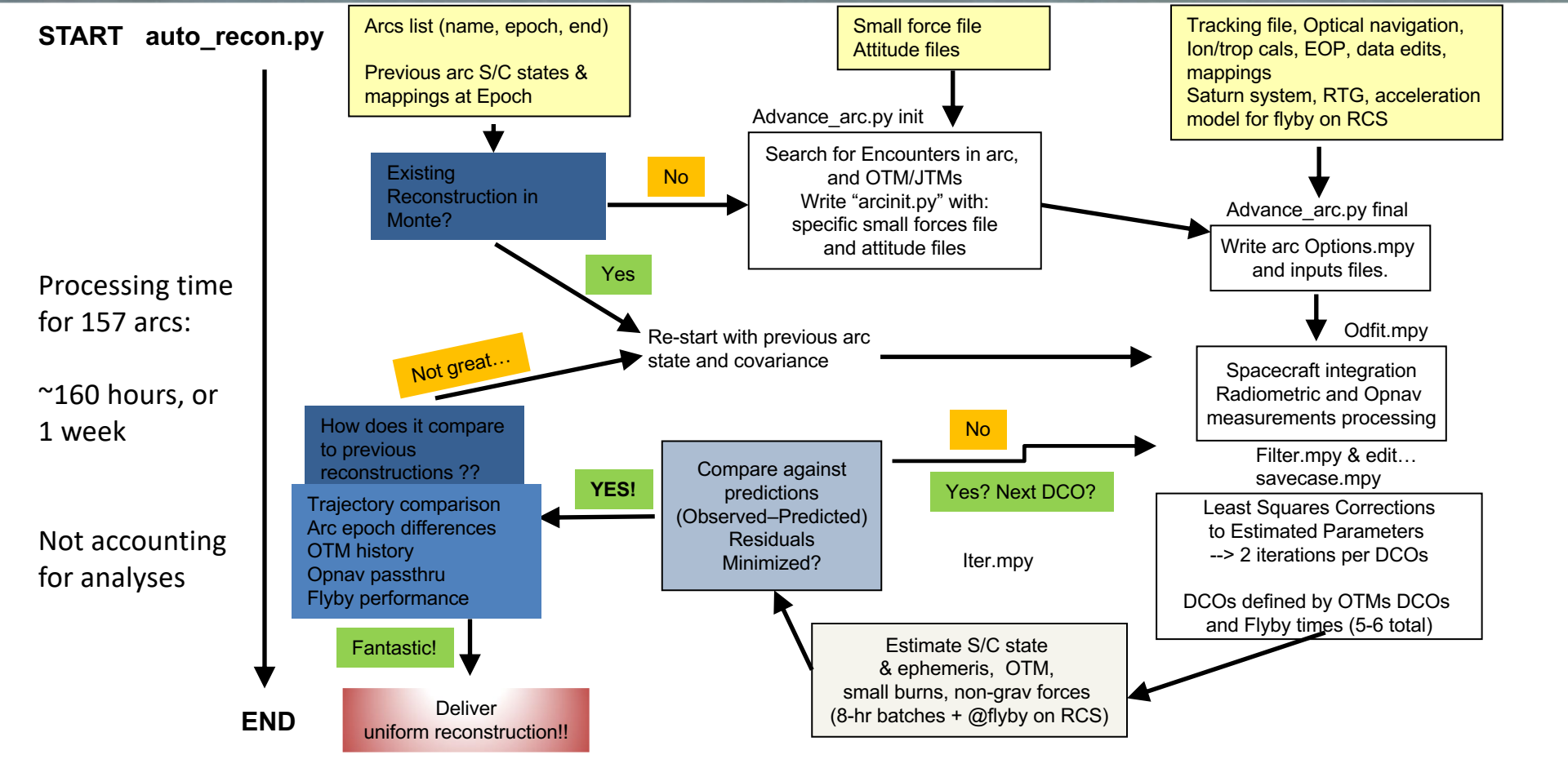



START auto_recon.py
Arcs list (name, epoch, end)
Previous arc S/C states & mappings at Epoch
Small force file
Attitude files
Tracking file, Optical navigation, Ion/trop cals, EOP, data edits, mappings
Saturn system, RTG, acceleration model for flyby on RCS
Advance_arc.py init
Existing Reconstruction in Monte?
No
Search for Encounters in arc, and OTM/JTMs
Write "arcinit.py" with: specific small forces file and attitude files
Advance_arc.py final
Write arc Options.mpy and inputs files.
Yes
Re-start with previous arc state and covariance
Not great…
Odfit.mpy
Spacecraft integration
Radiometric and Opnav measurements processing
How does it compare to previous reconstructions ??
Trajectory comparison
Arc epoch differences
OTM history
Opnav passthru
Flyby performance
YES!
Compare against predictions (Observed–Predicted) Residuals Minimized?
No
Yes? Next DCO?
Filter.mpy & edit… savecase.mpy
Least Squares Corrections to Estimated Parameters
--> 2 iterations per DCOs
DCOs defined by OTMs DCOs and Flyby times (5-6 total)
Iter.mpy
Estimate S/C state & ephemeris, OTM, small burns, non-grav forces (8-hr batches + @flyby on RCS)
Fantastic!
END
Deliver uniform reconstruction!!
Processing time for 157 arcs:
~160 hours, or 1 week
Not accounting for analyses

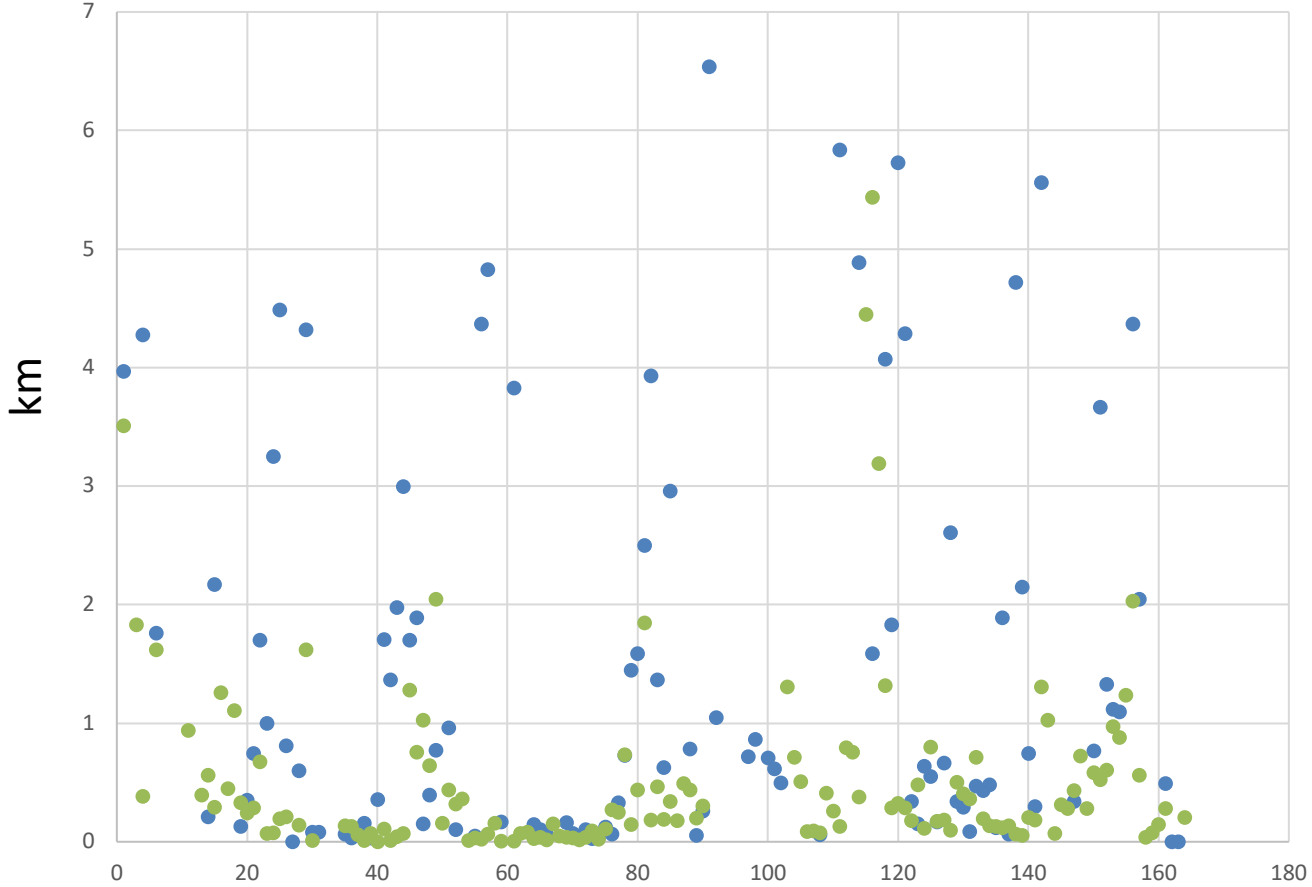
Preliminary Results

- Plan is for 4 different reconstructions to look at performance of different Saturn system model
  - The latest Saturn's model update delivered and used by the Cassini Navigation team in operations, sat389.
  - The Saturn system model estimated by the OD team until the last Titan flyby, T126.
  - The Saturn system model estimated by the OD team, including the very last close approach of Saturn during the Grand Finale.
  - The best and greatest Saturn system model from the SSD group (received in April 2018).
- One uniform reconstruction will be delivered

- Comparisons between those solutions include trajectory differences against the existing trajectories, trajectory differences at arc epochs for the newly reconstructed solutions, estimates of OTMs, and pass thru of optical navigation pictures against those trajectories.

- We expect higher position and velocity deviations from original reconstructions at beginning of Tour :
  - So far, average: position ~ 7 km; velocity ~150 mm/s until T16, then less than 4.5 km and 70 mm/s
  - Handful of outliers to investigate (where the fit didn't fail but large difference seems unrealistic)

Trajectory Differences at Epoch



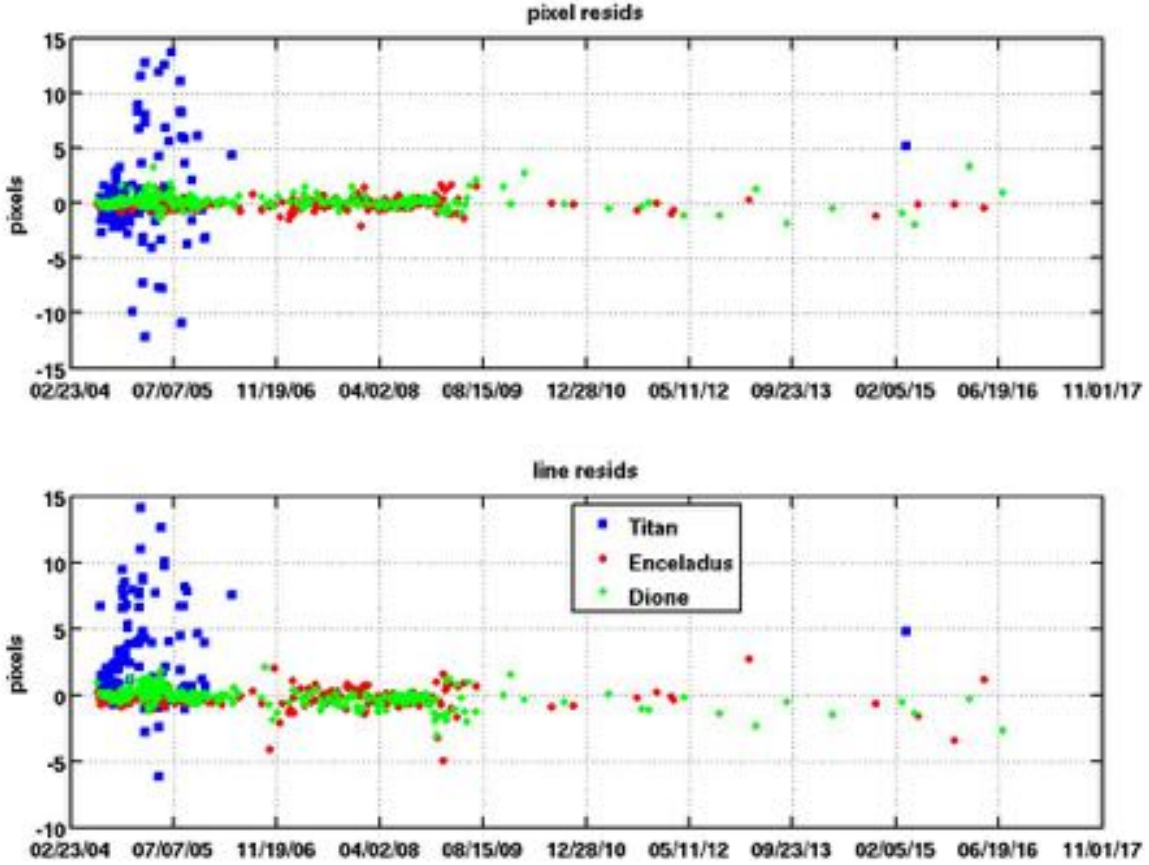
Trajectory position differences at each arc epoch, in kilometers, between two adjacent trajectories.

Comparing sat389 against reconstructions delivered during operations.

Legend:

- Reconstructions using Saturn system model “sat389”
- Reconstructions delivered during operations

Optical Navigation Residuals



Optical navigation residuals for Titan, Enceladus, and Dione, with pixel residuals shown on top and line residuals shown in the lower figure.

Looking at the computed image observables against the raw observables without filter corrections, or “pass thrus”, can help find biases in Saturn’s satellites positions or their centerfinding techniques.

Slight bias in Titan’s residuals, shown by the blue dots in the lower figure (line residuals). This bias likely corresponds to difficulties in its centerfinding due to the presence of its thick atmosphere.

Same trend for sat389, with larger outliers.

Conclusions

- The Cassini mission has been feeding the scientific communities for the last two decades, and the spacecraft disposal in Saturn's atmosphere in September 2017 will be a topic of research for likely another decade.

- Although trajectory reconstructions are currently publicly available, this uniform reconstruction will satisfy a need from the science teams for a uniform reconstruction using a single uniform model of the Saturn pole, gravitational field, and its satellite ephemerides.
  - This will allow utmost science analyses of instrument data obtained throughout the mission.

- Preliminary analyses show a general agreement with delivered reconstructions made during operations, although the current case shown, sat389, is not the best reconstruction fit.
  - Currently investigating sat409.
- We also observe a bias in Titan's observations which indicates the difficulty in centerfinding techniques for body with an atmosphere.
  - This will be feeding future mission strategies in using optical navigation and autonomous navigation systems.

- The Cassini uniform reconstruction is to be fully completed by the end of this year, and published through the NAIF website.